

Deeply Virtual Compton Scattering and Skewed Parton Distribution

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Abstract. An overview of the current status of and possible future theoretical, phenomenological and experimental studies of DVCS and SPD's is presented.

INTRODUCTION

The study of the structure of the nucleon is one of the most important frontiers in strong interaction physics. There are still many unanswered questions largely due to the non-perturbative nature of the bound state problem in QCD. Two traditional types of observables have been studied extensively, both theoretically and experimentally, for the last forty years: the parton (quark and gluon) distribution functions (PDF's) (via deeply inelastic scattering (DIS) or Drell-Yan processes), and elastic form factors of the nucleon. In the past few years, studies of a new type of nucleon observable, the skewed parton distributions (SPD's), have flourished(eg, [1]). The SPD's generalize and interpolate between the ordinary PDF's and elastic form factors and therefore contain rich structural information. They can be measured in (exclusive) diffractive processes in which the nucleon recoils elastically after receiving a non-zero momentum transfer in the so-called deeply virtual limit².

THEORY: FROM DIS & PDF'S TO DVCS & SPD'S

Ordinary PDF's in DIS are accessed through an optical theorem that relates the imaginary part of a forward (Compton) scattering amplitude to the cross section. Through operator product expansion (OPE) one factorizes the hard scattering from the soft physics. The hard scattering can be calculated order by order in perturbation theory while the soft part is parametrized as PDF's. They are essentially matrix elements of light-cone bilocal (quark and gluon) operators between equal momentum (symmetric) states. The factorization scale dependence of the matrix

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²⁾ $Q^2 \rightarrow \infty$ while keeping Bjorken variable $x = x_B = \frac{Q^2}{2p \cdot q}$ fixed, and $Q^2 \gg t = -(p' - p)^2$ where p (p') is the initial(recoil) nucleon momentum.

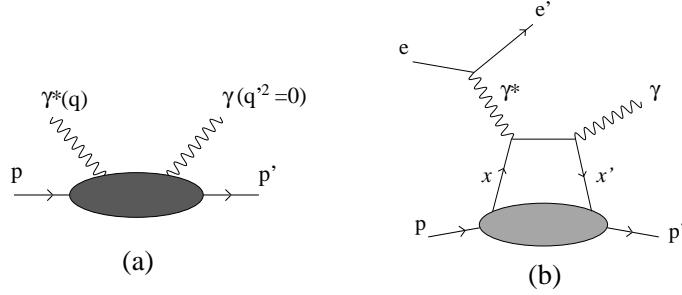


FIGURE 1. The DVCS process

elements/PDF's is governed by a renormalization group equation. The cross section is related to (usually a linear combination of) PDF's.

The SPD's are, on the other hand, essentially matrix elements of the same light-cone bilocal operators between *different* momentum (asymmetric) states. They can be accessed thus via deeply virtual processes like diffractive vector meson production ($ep \rightarrow ep' VM$) [2–5] and deeply virtual Compton scattering (DVCS) [6–8]. DVCS(See fig.1. (b) is the lowest order “handbag” diagram in an e-p collision, where x and x' denote the longitudinal momentum fractions of the interacting parton,) is a non-forward process signified by non-zero t with the longitudinal momentum (fraction) transfer $x-x' \equiv \zeta = x_B$ and also in general a non-zero transverse momentum transfer.

One still has valid factorization theorem [4,9] and OPE [6,10] (fig.2) in the non-forward case. That is, the DVCS amplitude can be factorized into a hard scattering part calculable perturbatively (the upper part of the OPE diagram and also a crossed term) and a soft part (lower part of the diagram) parametrized as SPD's.

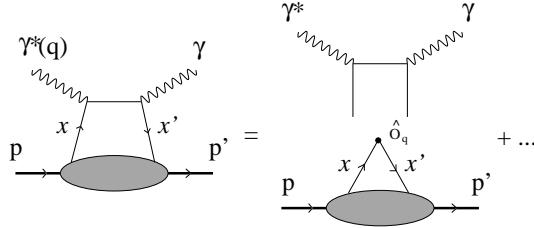


FIGURE 2. Non-forward OPE (only the lowest $q-q$ diagram is shown)

SPD's, like usual PDF's, depend on factorization scale. Its QCD evolution is governed again by a renormalization group equation through a kernel that has been worked out to next-to-leading-order (NLO) [11].³ The QCD Q^2 evolution of the SPD's has been studied extensively and has been shown to exhibit characteristics of both the DGLAP evolution of usual PDF's and the ERBL evolution of meson distribution amplitudes, depending on different kinematic regions(eg, [1,10]). In particular, in the small x_B , ie, small $\xi = \frac{x_B}{2(1-x_B/2)}$ region SPD's are closely connected with usual PDF's [4]. For $x \gg \xi$, SPD's \approx PDF's, while for $x \sim \xi$, in leading

³⁾ Also worked out is the NLO correction to hard scattering in DVCS.

$\log \frac{1}{x} \sim \log \frac{1}{\xi}$, SPD's \rightarrow forward PDF's [2] and at large factorization scale the Q^2 evolution tends to wash out effects of the asymmetry ξ (eg, [12]). The region $x < \xi$ is least well-known.

SPD's are indeed form factors of the non-forward scattering amplitude $\gamma^* p \rightarrow \gamma p'$, eg, take quarks (similar for gluons)

$$\begin{aligned} FT \langle p', s' | \bar{\psi}(0) \gamma^\mu \psi(z) | p, s \rangle &= H(x, \xi, t) \bar{u}(p', s') \gamma^+ u(p, s) \\ &+ E(x, \xi, t) \bar{u}(p', s') \frac{i\sigma^{+\nu}(p' - p)_\nu}{2M} u(p, s) + \dots, \quad (\text{Quark Spin Sum}) \\ FT \langle p', s' | \bar{\psi}(0) \gamma^+ \gamma_5 \psi(z) | p, s \rangle &= \widetilde{H}(x, \xi, t) \bar{u}(p', s') \gamma^+ \gamma_5 u(p, s) \\ &+ \widetilde{E}(x, \xi, t) \bar{u}(p', s') \frac{(p' - p)^+ \gamma_5}{2M} u(p, s) + \dots, \quad (\text{Difference}) \end{aligned}$$

where $H(x, \xi, t)$, $E(x, \xi, t)$, $\widetilde{H}(x, \xi, t)$, $\widetilde{E}(x, \xi, t)$ are skewed quark distributions with $2\xi = \frac{x_B}{1-x_B/2}$ ⁴ and FT denotes Fourier Transform.

While in general two SPDs correspond to one usual PDF, in the forward limit of $p = p'$ ($\xi \rightarrow 0$ and $t \rightarrow 0$), SPD's are reduced to the normal distributions: $H(x, 0, 0) = q(x)$, $\widetilde{H}(x, 0, 0) = \Delta q(x)$, where $q(x)$ and $\Delta q(x)$ are the conventional forward quark and quark helicity distributions (Similar equations hold for gluons). At the same time, the first moments of these SPD's are related to nucleon form factors of corresponding EM or Axial currents by the sum rules:

$$\begin{aligned} \int_{-1}^1 dx H(x, \xi, t) &= F_1(t), \quad \int_{-1}^1 dx E(x, \xi, t) = F_2(t), \\ \int_{-1}^1 dx \widetilde{H}(x, \xi, t) &= G_A(t), \quad \int_{-1}^1 dx \widetilde{E}(x, \xi, t) = G_P(t). \end{aligned}$$

At the same time, SPD's have many new features, in contrast to the usual PDF's.

- The non-forward amplitude to lowest $O(\alpha_s)$ is generally related to a integration over the SPD's of type $Amp \sim \int dx \frac{1}{x - \zeta + i\epsilon} f(x, \zeta, t)$ (f denotes SPD's).
- Cross section is obtained by squaring the amplitude. There is not an optical theorem, nor a simple probability interpretation. SPD's can be viewed as overlap of wavefunctions between different parton numbers (Fock states) [13]
- SPD's are interference/correlation functions of different wave functions/ probability amplitudes. The extreme case with $x > 0$ and $x' < 0$ can be understood by re-interpret x' line as antiparton with momentum fraction $-x'$ resulting in "extracting $q\bar{q}$ -pair" from the nucleon.

SPD(via DVCS) is the only place so far probing the orbital angular momentum of partons [7]. Moments of the SPD's provide information on quark and gluon

⁴⁾ Notations in the literature differ. That of Ji's is used and mom. fractions refer to $\frac{1}{2}(p+p')$.

contributions to nucleon's spin because they are closely related to the form factors of the (QCD) energy-momentum tensor. For example, one can measure the skewed quark distribution in spin-averaged experiments and extract form factors of the tensor. Extrapolating to $t = 0$ one can obtain the total (spin+orbital) quark contribution to the nucleon spin $J_q(0)$ by taking $t = 0$ in Ji's sum rule:

$$\frac{1}{2} \int dx x (H_q(x, \xi, t) + E_q(x, \xi, t)) = J_q(t).$$

There is a similar sum rule for gluon and one finds $J_q(0) + J_g(0) = \frac{1}{2}$.

PHENOMENOLOGY AND EXPERIMENTS

Using known usual PDF's as input, models of SPD's have been studies by making ansatz that fulfills the (some of which very non-trivial) general properties of SPD's (eg, [1,14]). There are also studies on contributions from meson exchange in the ERBL region ($x > 0, x' < 0$, on SPD's as overlap of proton wavefunctions for $x > \xi$ [15] and on different dynamical models of SPD's, including bag model, instanton vacuum and quark soliton model (eg, [16]).

Experiments usually access integrals of SPD's with parton momenta that are multi-variable and can not be directly obtained from cross sections. Thus two main issues remain, one being experimental difficulty, the other extracting SPD's from data.

The key background to DVCS is the QED Bethe-Heitler(BH) process (Compton scattering), which depend on EM form factor, and its interference with DVCS. At higher Q^2 the background is smaller, but so is the signal. This makes measuring DVCS cross section very difficult experimentally. The first experimental measurement come from HERA [17], where the preliminary on 96/97 data has shown evidence of the DVCS signal. However, the interference also makes possible exploring DVCS at the amplitude level, measuring its imaginary and real part independently.⁵ There has been a lot of data on vector meson production (eg, [19,20]), but the extraction of SPD's is still a pending task.⁶ Table 1 is a very brief overview of the current experimental status.

Independent of the actual form of SPD's, factorization predicts that in the scaling limit of $Q^2 \rightarrow \infty; x_B, t$ fixed, DVCS $\sim \frac{1}{Q^6}$ and VM production $\sim \frac{1}{Q}$. There are also

⁵⁾ A proposal for JLAB Hall A [18] proposed measuring cross section difference for leptons of opposite helicities, which is proportional to the interference of the imaginary part of the DVCS amplitude with a known BH weight. This quantity turns out to be a *linear* combination of SPD's, thus if scaling is reached at the kinematic region with 6Gev beam, it would be a measurement of SPDs' contribution. Also since the higher twist effects is only down $\frac{1}{Q}$ and has a different angular distribution (thus not masked by leading-twist) it can give an estimation of these effects.

⁶⁾ Another reason of the interest in exclusive diffractive VM at small-x is that the cross section is predicted to be proportional to the *square* of gluon density [2]. This could be a direct measurement of the glue in the proton, rather than getting it from evolution as in DIS.

TABLE 1. Overview of Status of SPD-related Exps, DVCS and VM Production

Process(es)	DATA	Proposed
DVCS	HERA [17] ($e^+p \rightarrow e^+\gamma p'$)	COMPASS, HERMES, JLAB [18]
Meson Prod.	HERMES [19], HERA [20]	JLAB, COMPASS

helicity selection rules stating that for DVCS only $\gamma^*(T) \rightarrow \gamma(T) \sim \frac{1}{Q^0}$ and $\gamma^*(L) \rightarrow \gamma(T)$ is power suppressed while for VM only $\gamma^*(L) \rightarrow VM(L) \sim \frac{1}{Q}$ and all else are power suppressed. This is due to helicity conservation and introduces helicity parton distributions (eg, helicity flip gluon distribution that has no counterpart in DIS) [21], while being higher-twist gives the suppression. Therefore by looking at the angular distributions one have a window on higher-twist effects [22] since it is not masked by leading twist because of different helicity.

Other SPD-related experimental processes been proposed include diffractive di-jets (photo-production) and crossed DVCS (eg, $\gamma^*\gamma \rightarrow \pi^+\pi_-$) [23], etc.

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